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Biaxial shear in RC square beams: Experimental, numerical and analytical program

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ABSTRACT

There are limited studies about the effect of biaxial shear in reinforced concrete (RC) elements. However, this load condition is quite common in columns subjected to horizontal forces. Moreover, the design and evaluation methods reported in codes do not consider any interaction between the shear strength in the two principal directions of inertia.

This paper presents the results of an experimental program on six beams, with square section, subjected to inclined shear, which have been tested in order to understand the influence of the load inclination on the shear failure envelope.

Based on the experiments, a new analytical formulation was proposed, with the aim to extend the prescriptions presented in fib-Model Code 2010 and ACI Code to the biaxial shear force.

The proposed formulation was finally validated against results from experiments and non-linear finite element analyses (NLFEA).

1. Introduction

The study of the behavior of RC elements subjected to biaxial shear was seldom investigated in literature. While there are several models that allow to properly evaluate the biaxial bending, only few codes, like the Japanese JSCE code [1,2] provide formulations for the design shear resistance of RC members subjected to biaxial shear. Many building codes (i.e. ACI Code [3], Eurocode 2 [4], Eurocode 8 [5] and Italian Building Code [6]) and current guidance (i.e. fib-Model Code 2010 [7]) do not report recommendations about the design and evaluation of biaxial shear.

However, the adoption of the Hierarchy Resistance Criterion result in a significant increase of the shear bearing capacity required by columns, thus becoming critical in the design process [8].

The deficiency of code references concerning the biaxial shear is particularly critical for the evaluation and rehabilitation of existing structures: a large number of buildings, constructed before the introduction of the seismic design in codes, presents in fact very low amounts of shear reinforcement.

The indeterminacy in the direction of the seismic action represents a major problem in the design phase: the variable-angle truss model [9,10], useful for the evaluation of shear resistance in case of uniaxial action, is not directly applicable to a biaxial load condition. In addition, from the decomposition of the shear load along the two principal directions and the comparison with the relative uniaxial shear strengths, the truss model may results in a dangerous overestimation of the actual bearing capacity [8].

The analysis of the literature [1,2,8,11–17] clearly shows the difficulties in formulating simple and consistent models. Even considering the case of square section, the parameterization of the geometric properties with respect to a generic direction of loading is rather complex. The influence of the longitudinal rebars on the shear and flexural behavior also differs with the change in load direction; moreover, the presence of skin reinforcement introduces further complications.

In literature, there is a general agreement about the inaccuracy of models based on the decomposition of the shear force into its main components and the superposition of the effects [8].

Mark [11] proposed a revision of the truss model, considering a spatial distribution, which allows considering the increase of stresses in the stirrups, in the longitudinal bars and in the concrete with the variation of the load inclination. Using a number of dimensionless factors of interpolation, Mark generalized the formulas for $V_{R,c}$ (compression strut) and $V_{R,s}$ (shear reinforcement) proposed in the

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Eurocode 2 [4]. Moreover, an experimental program on 25 full size concrete beam and an exhaustive series of numerical analyses were carried out to validate the proposed model [12–15].

Experimentally, Yoshimura and Tsumura [16] carried out a number of tests on squat concrete columns. The test set-up was specifically designed in order to apply an inclined load and a compressive force on the column (the latter to simulate the axial force). The experimental results evidenced that the resistant domain is a quadratic function of the load angle.

Hansapinyo et al. [17] focused on the experimental study of the biaxial shear behavior of RC elements with square and rectangular section; firstly, specimens with square section were tested. The results confirmed, in agreement with Yoshimura and Tsumura [16], the quadratic shape of the resistant domain. Subsequently, experiments concerned rectangular beams. The authors compared the results with the predictions of the Japanese JSCE code [1,2], which resulted conservative. This over-strength, however, tended to decrease with increasing of load inclination. The authors highlighted an overestimation of the shear resistance provided by the transverse reinforcement ($V_{R,s}$) for values close to 45°, noting the need for a better modeling of the truss resistant mechanism in case of biaxial shear.

Within this contest, this paper aims at experimentally investigating the biaxial shear behavior in square beams representing typical existing shear critical columns. A 3D truss model, extending the work of Mark [11], for evaluating the biaxial shear strength, was analyzed and modified towards the proposal of new formulations, extending the prescriptions of *fib*-Model Code 2010 [7] and ACI Code [3].

The proposed formulations were validated against results from experiments and NLFEA.

2. Experimental program

2.1. Specimen geometry

The experimental program concerned six full-scale beams (Fig. 1a) tested under a four point loading system with a shear span-to-depth ratio a/d_{eff} from 3 to 3.6, being rather critical under shear. Three different load inclinations with respect to the principal directions of inertia were considered: 0° (uniaxial loading, with a/d_{eff} = 3 and a = 650 mm), 22.5° (a/d_{eff} = 3.6 and a = 850 mm) and 45° (a/d_{eff} = 3.4 and a = 920 mm), as depicted in Fig. 1.

The length of the effective depth (d_{eff}) refers to the distance between the resultant tensile force of the longitudinal bars and the upper limit of the compressed concrete zone (Fig. 1b), measured perpendicularly to the neutral axis and assuming a cracked flexural behavior.

Two specimens were tested for each inclination: one without shear reinforcement (S0 Type) and one with a minimum amount of stirrups (S6 Type: ∅6 mm @ 250 mm, corresponding to a shear reinforcement ratio of 0.08%). The latter does not satisfy the minimum requirements for shear reinforcement and therefore a quite brittle failure is expected, due to a partial activation of stirrups. However, this little reinforcement was selected because it is representative of a typical critical shear reinforcement for existing RC columns constructed between the 40 s and the 70 s. The designation of the typology (either S0 or S6) is then followed by the inclination angle to properly identify any specimen.

Fig. 1c illustrates the cross section geometry and the reinforcement details for both typologies: all the beams were 3000 mm long and presented a 300 × 300 mm cross section. The longitudinal reinforcement consists of 8∅20 mm rebars, A_s = 2513 mm^2, arranged along the whole perimeter (three on each side), resulting in a reinforcement ratio of 2.79%.

2.2. Material properties

All the beams were made with the same concrete. The mix design consisted in 430 kg/m^3 of Cement Portland II/A-LL 42.5R and 168 kg/m^3 of water, resulting in a water/cement ratio (w/c) of 0.39. The maximum aggregate size was 14 mm. An amount of 3.85 kg/m^3 of super-plasticizer was added to the concrete in order to improve the workability. According to European Standard EN 12350-2 [18], the concrete showed a S4 consistency class.

In accordance with EN 12390-13 [19] and EN 12390-3 [20], six cylinders 80(Ø) × 210 mm and twelve 150 mm cubes were used for the determination of the Modulus of Elasticity and the Cubic Compressive Strength of concrete, respectively. At 28 days, the secant Young's modulus, E_{cm}, was 34.5 GPa, while the cubic compressive strength, R_{cm} 54.04 MPa. The cylinder compressive strength of concrete was analytically derived as $f_{cm} = 0.83\ R_{cm} = 44.85$ MPa.

Rebars properties were evaluated according to EN 15630-1 [21]; the yielding and ultimate tensile strength resulted 522 MPa and 639 MPa respectively.

The mean tensile strength of the concrete was evaluated according to EC2 [4] as:

$$f_{ctm} = 0.30 f_{ck}^{2/3} = 3.32\ \text{MPa} \tag{1}$$

where f_{ck} is the characteristic cylinder compressive strength of concrete ($f_{ck} = f_{cm} - 8$ MPa = 44.85 − 8 = 36.85 MPa).

2.3. Test set-up and instrumentation

In order to carry out a displacement controlled test, an electromechanical actuator, with a loading capacity of 1000 kN, was used. In the test loading frame (Fig. 2), the actuator was hanged at the laboratory strong floor and the load transferred to the top through transverse steel beams (two 2-UPN400) and 32 mm dywidag rebars. The applied load was measured by two load cells, placed between the bearing steel plates of the dywidag bars and the upper 2-UPN400 beam.

For the elements with an inclination of 22.5° and 45°, specific RC elements were designed in order to properly rotate the beams, being the load applied vertically. These elements were 250 mm wide both for supports and loading points and were designed so that two sides of the square section be totally loaded, to prevent load concentration (Fig. 3a). In order to ensure a uniform stress transfer, bedding mortar was placed between the blocks and the beam. Fig. 3a and b presents the details for the 22.5° inclined element and a view of the S6-45 specimen prior to testing.

For the specimen with zero inclination, a normal 4 point loading test was carried out with a classical steel roller and a steel hinge. 25 mm thick layers of neoprene guaranteed the load distribution.

Linear Variable Differential Transformers (LVDTs) were utilized for measuring the mid-span deflection (front and back side) and the support displacements. Potentiometric Transducers measured shear and flexural crack widths and top chord shortening at mid-span.

In the beams with an inclination equal to 0°, the transducers for shear crack widths were installed with an inclination of 135° to the horizontal line. In the specimens rotated 45°, the shear crack pattern affects every side of the beams; because of that, a transducer was placed on each face of the element. Finally, in the beams with an inclination of 22.5°, a couple of transducer were placed on the upper face inclined 67.5°, and none on the lower face inclined 22.5°.